

# *First Run II Measurement of the W Boson Mass with CDF*



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on behalf of the CDF Collaboration

Lake Louise Winter Institute  
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# Outline

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2. W Production at the Tevatron
3. Analysis Strategy
4. Detector Calibration
  - Momentum Scale
  - Energy Scale
  - Recoil
5. Event Simulation
6. Results
7. Summary/Outlook



# Motivation

- Derive W mass from precisely measured electroweak quantities

$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)}$$

$$\cos \theta_W = \frac{m_W}{m_Z}$$

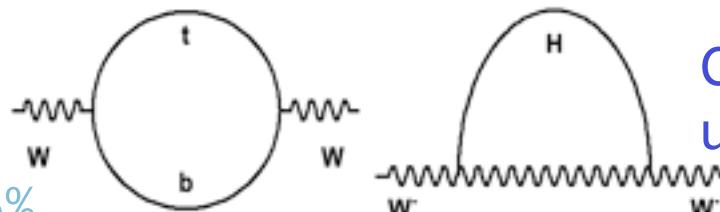
- Radiative corrections  $r$  dominated by top quark and Higgs loop  
 $\Rightarrow$  allows constraint on Higgs mass

Current top mass

uncertainty 1.2%

(2.1 GeV)

$\rightarrow$  contributes 0.016%  
(13 MeV) to  $\delta M_W$



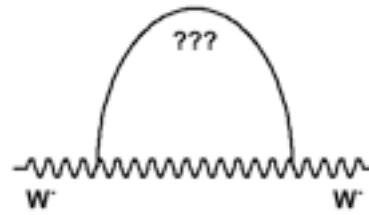
Current W mass

uncertainty 0.036%

(29 MeV)

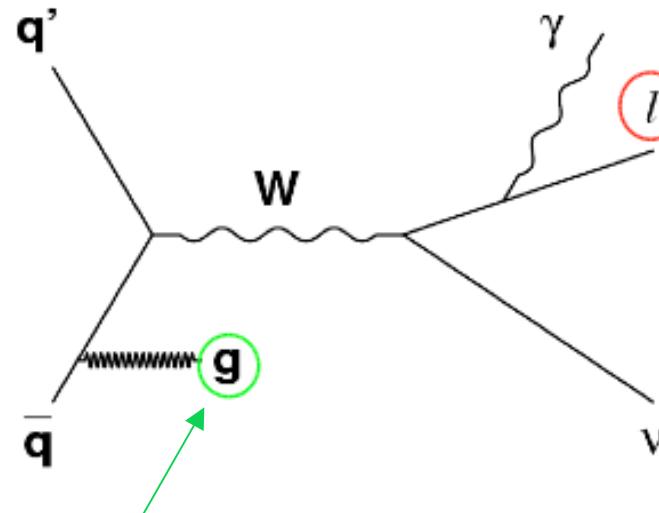
$\rightarrow$  Higgs mass predicted:  $85^{+39}_{-28}$  GeV

- Progress on W mass uncertainty now has the biggest impact on Higgs mass constraint
- With improved precision also sensitive to possible exotic radiative corrections



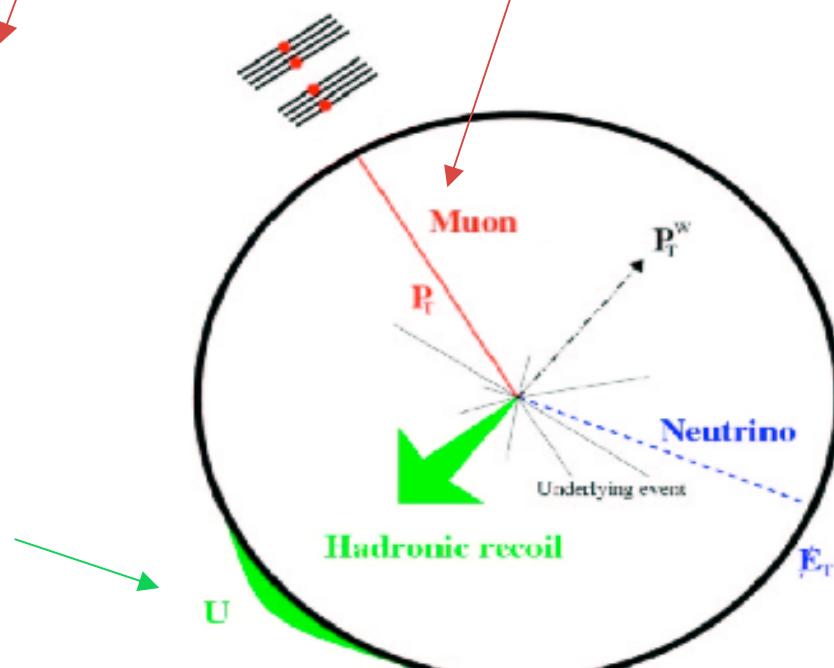
# *W Production at the Tevatron*

Quark-antiquark annihilation  
dominates (80%)



precise charged lepton measurement  
is the key (achieved  $\sim 0.03\%$ )

Recoil measurement allows  
inference of neutrino  $E_T$   
(restricted to  $u < 15$  GeV)

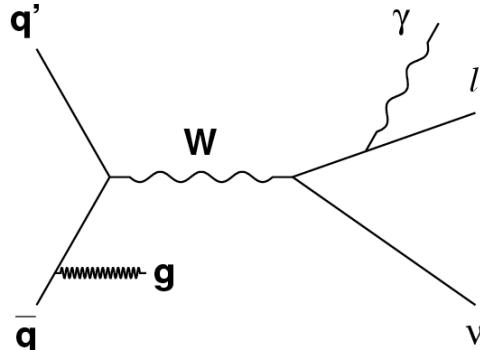


Combine information into transverse mass:  $m_T = \sqrt{2 p_T^\ell p_T^\nu (1 - \cos \phi_{\ell\nu})}$

Use  $Z \rightarrow \mu\mu$  and  $Z \rightarrow ee$  events to derive recoil model

# Measurement Strategy

W mass is extracted from transverse mass, transverse momentum and transverse missing energy distribution



## Detector Calibration

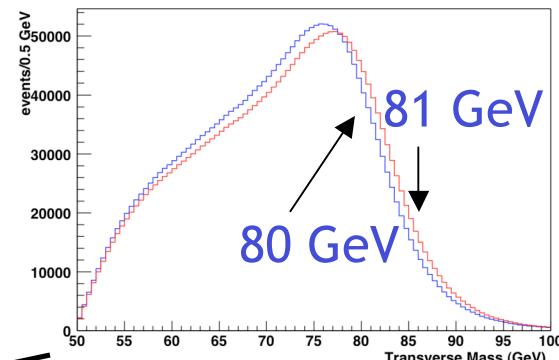
- Tracking momentum scale
- Calorimeter energy scale
- Recoil

Data

## Fast Simulation

- NLO event generator
- Model detector effects

## W Mass templates



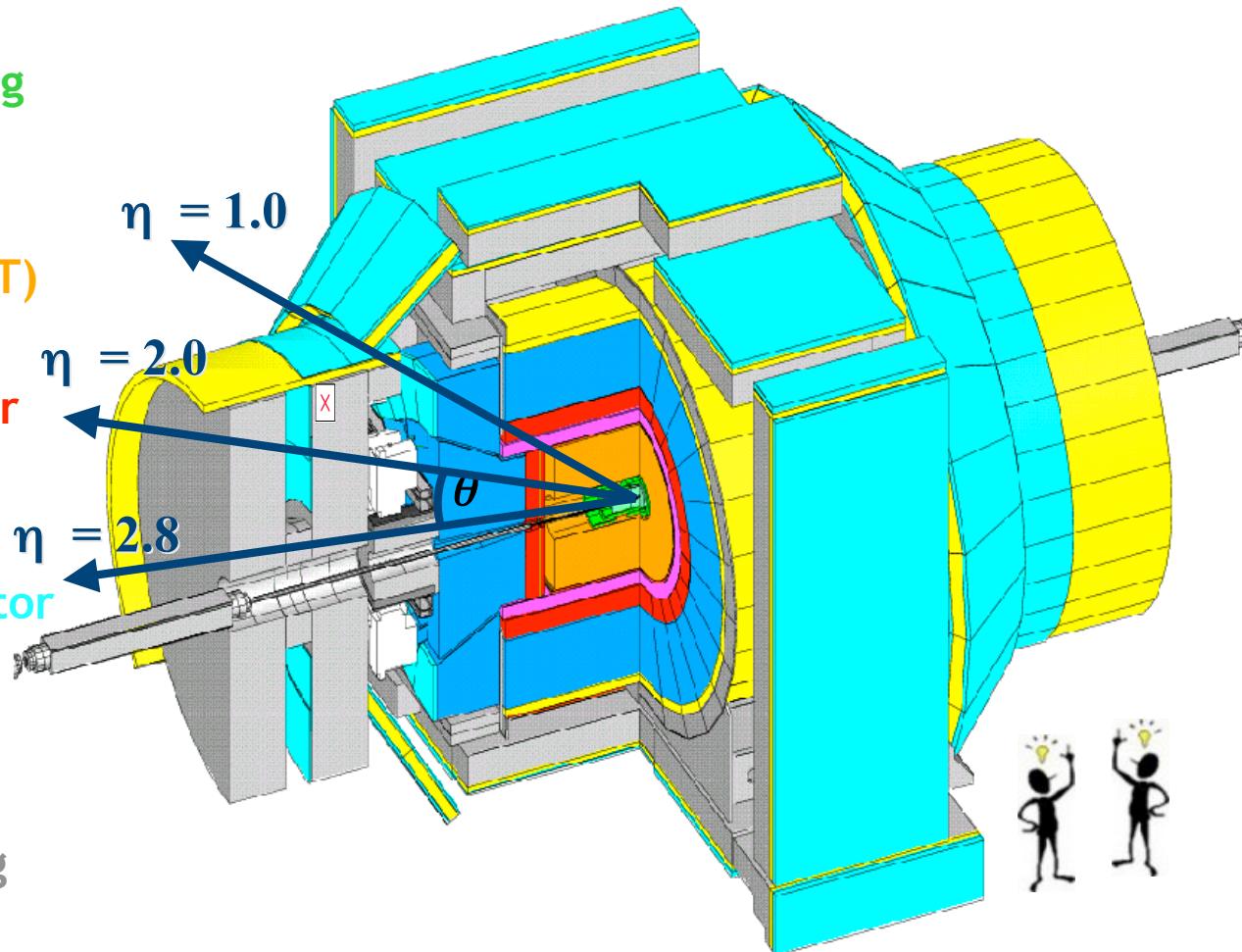
+ Backgrounds

## Binned likelihood fit

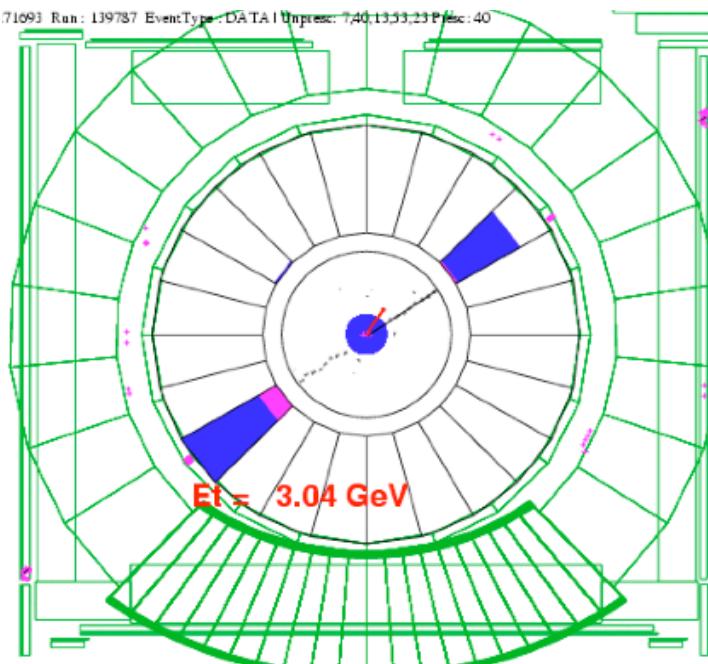
W Mass

## CDF Detector

- Silicon tracking detectors
- Central drift chambers (COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



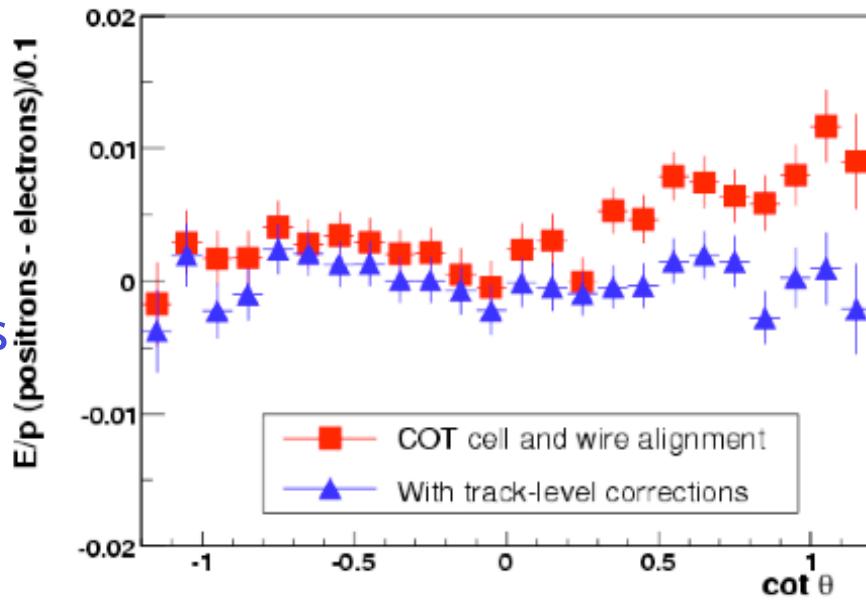
# Tracker Alignment



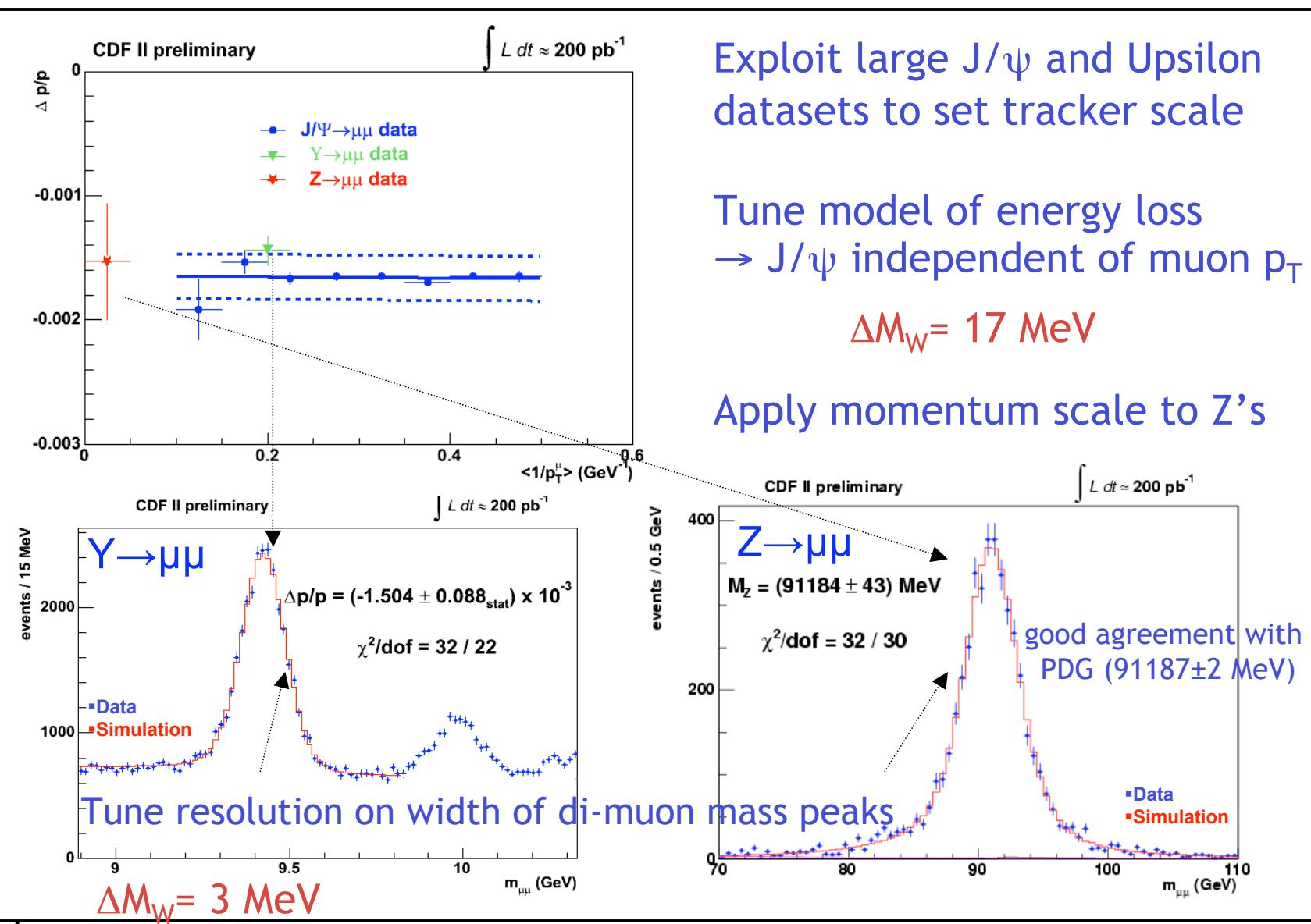
- Statistical uncertainty of track-level corrections leads to systematic uncertainty

$$\Delta M_W = 6 \text{ MeV}$$

- Internal alignment is performed using a large sample of cosmic rays  
→ Fit hits on both sides to one helix
- Determine final track-level curvature corrections from electron-positron E/p difference in  $W \rightarrow e\nu$  decays

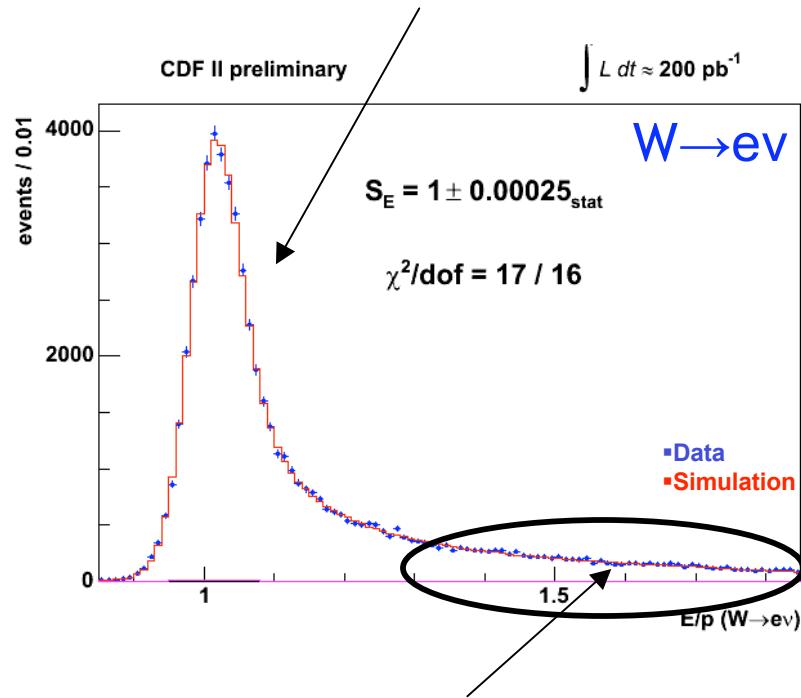


# Momentum Scale Calibration

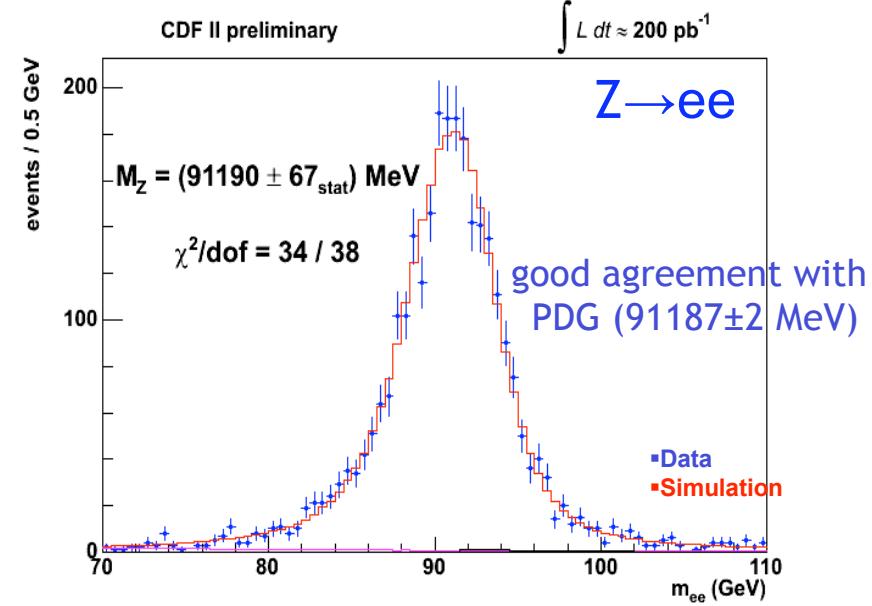


# Energy Scale Calibration

Transfer momentum calibration to calorimeter using E/p distribution of electrons from W decay by fitting peak of E/p



Apply energy scale to Z's



Tune number of radiation lengths with E/p radiative tail

Correct for calibration  $E_T$  dependence

Add Z Mass fit to calibration (30% weight)  $\Delta M_W = 30 \text{ MeV}$

Tune resolution on E/p and Z mass peak  $\Delta M_W = 9 \text{ MeV}$

# Hadronic Recoil Definition

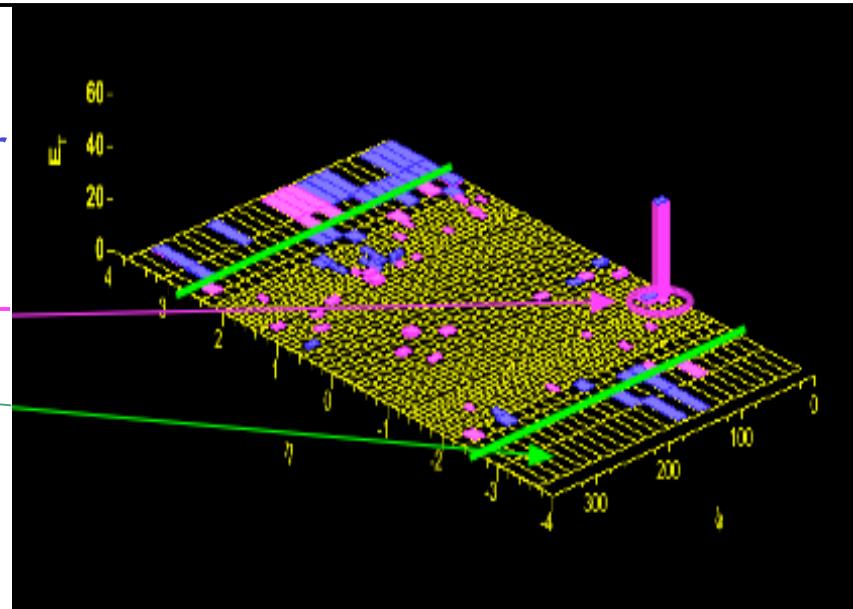
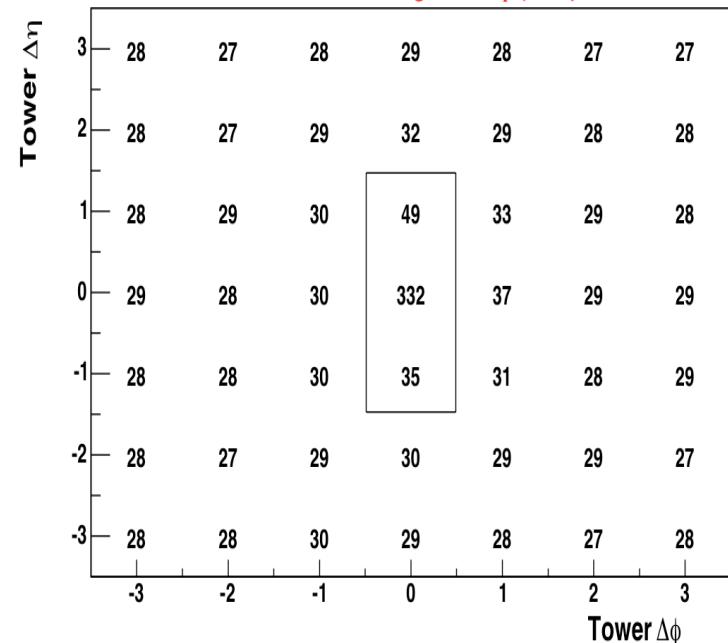
Recoil definition:

→ Vector sum over all calorimeter towers, excluding:

- lepton towers

- towers near beamline  
("ring of fire")

Muon Electromagnetic  $E_T$  (MeV)



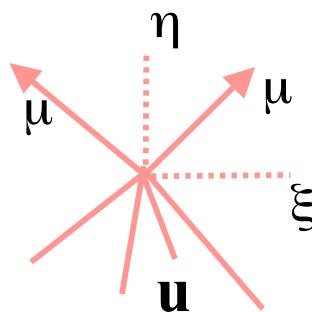
Electrons: Remove 7 towers keystone  
 $\Delta M_W = 8 \text{ MeV}$

Muons: Remove 3 towers (MIP)  
 $\Delta M_W = 5 \text{ MeV}$

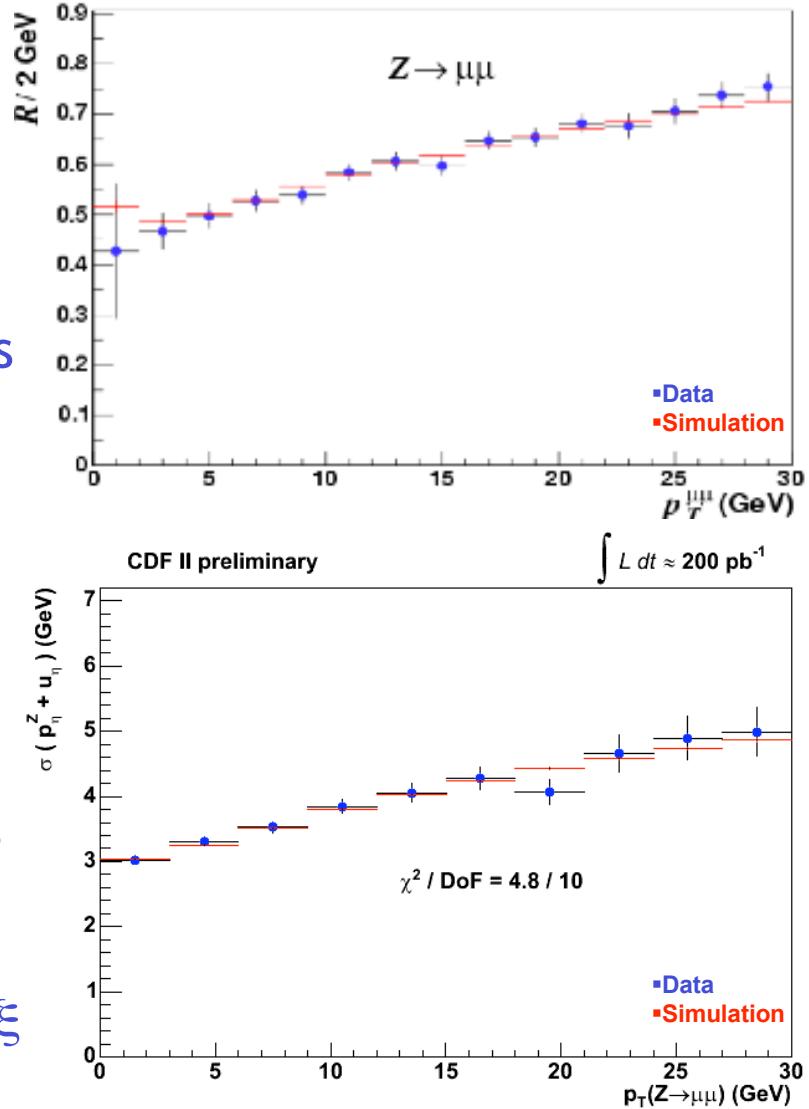
Model tower removal in simulation

# Hadronic Recoil Model Calibration

- Use Z balancing to calibrate recoil energy scale and to model resolution
- Calibrate scale ( $R = u_{\text{meas}} / u_{\text{true}}$ ) with balance along bisector axis  
 $\Delta M_W = 9 \text{ MeV}$

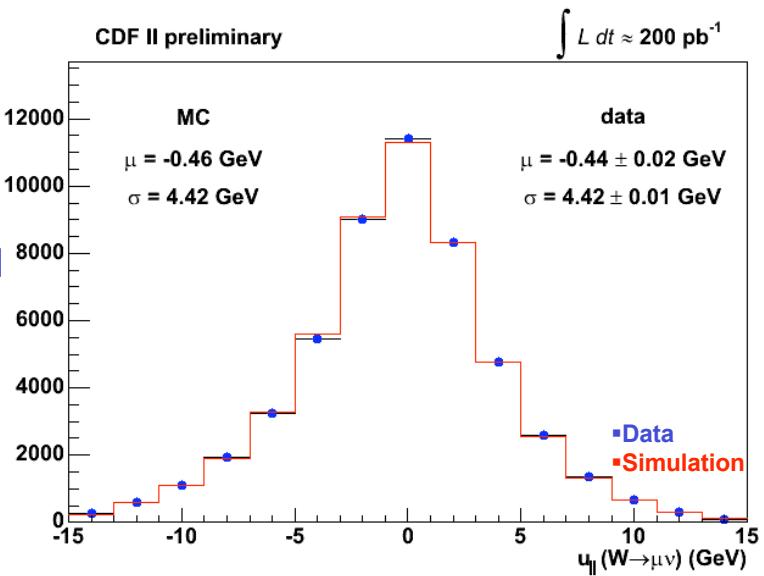
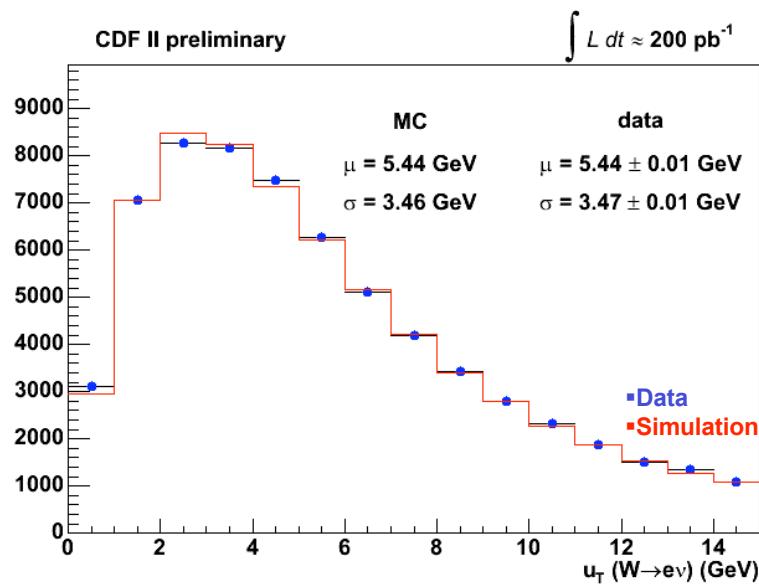


- Resolution has two components
  - soft (underlying event)
  - hard (jets)
- Calibrate along both axes,  $\eta$  &  $\xi$   
 $\Delta M_W = 7 \text{ MeV}$



# Recoil Model Checks

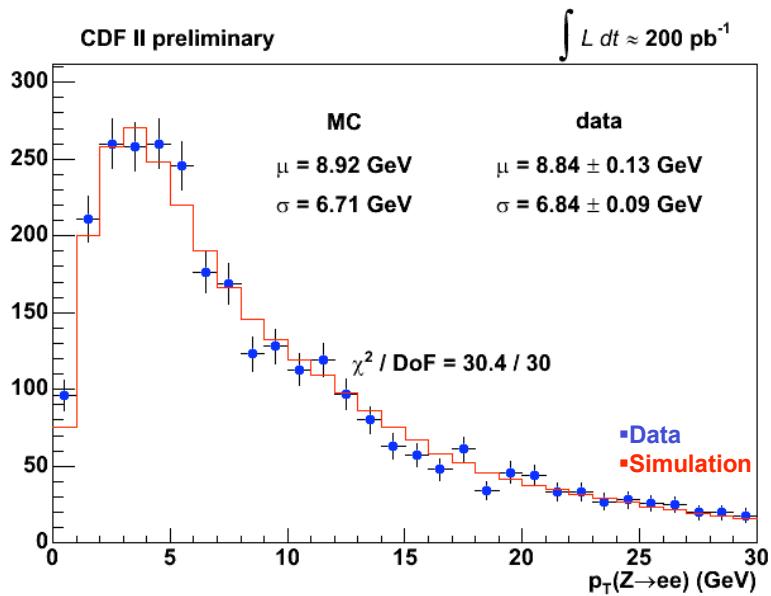
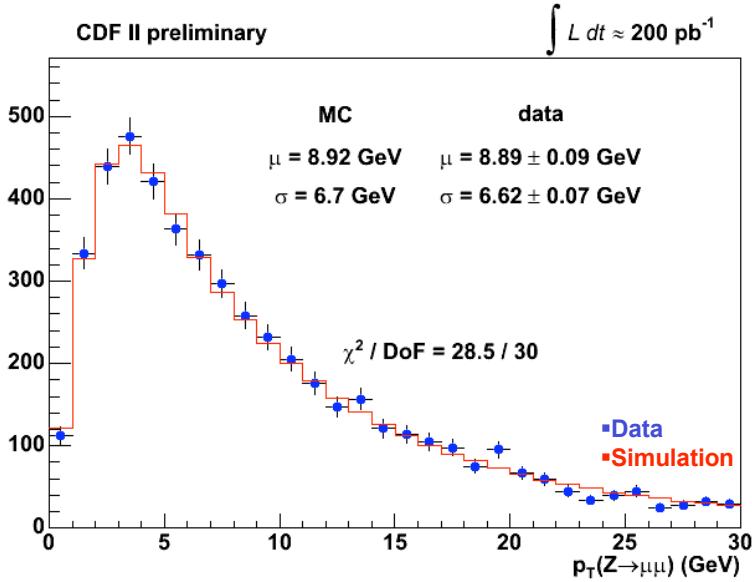
- Apply model to W sample to check recoil model from Z's
- Recoil projection along lepton  $u_{\parallel}$ 
  - directly affects  $m_T$  fits
  - Sensitive to lepton removal, scale, resolution, W decay



- Recoil distribution
  - sensitive to recoil scale resolution and boson  $p_T$
- Recoil model validation plots confirm consistency of the model

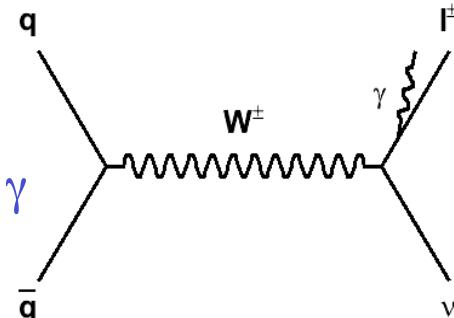
# Boson $p_T$ Model

- Model boson  $p_T$  using RESBOS generator [Balazs *et.al.* PRD56, 5558 (1997)]
- Non-perturbative regime at low  $p_T$  parametrized with  $g_1$ ,  $g_2$ ,  $g_3$  parameters



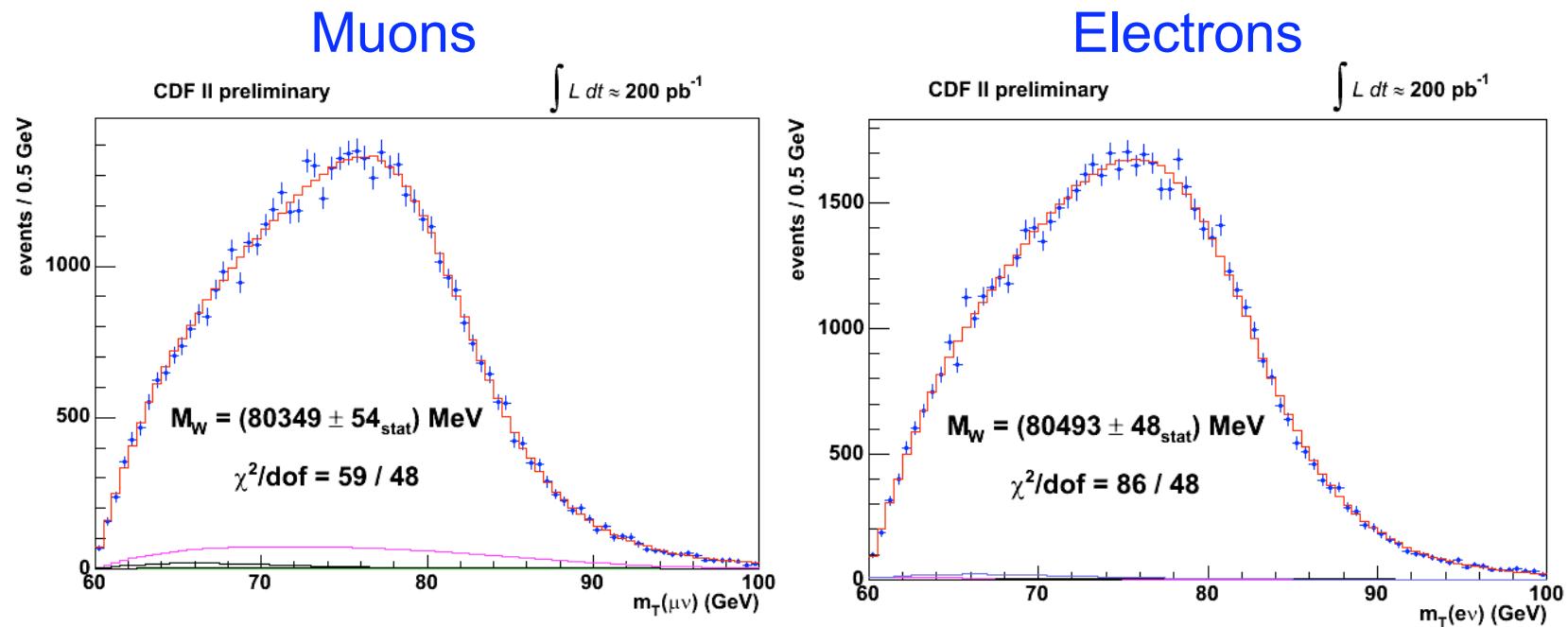
- $g_2$  parameter determines position of peak in  $p_T$  distribution
  - Measure  $g_2$  with Z boson data (other parameters negligible)
  - Find:  $g_2 = 0.685 \pm 0.048$
- $\Delta M_W = 3 \text{ MeV}$

# Production, Decay and Backgrounds

- QED radiative corrections:
    - use complete NLO calculation (WGRAD)  
[Baur *et.al.* PRD59, 013002 (1998)]
    - simulate FSR, apply  $(10\pm 5)\%$  correction for 2<sup>nd</sup>  $\gamma$   
 $\Delta M_W = 11 \text{ (12) MeV for } e \text{ (\mu)}$
  - Parton Distribution Functions:
    - affect kinematics through acceptance cuts
    - use CTEQ6 ensemble of 20 uncertainty PDFs  
 $\Delta M_W = 11 \text{ MeV}$
  - Backgrounds:
    - have very different lineshapes compared to W signal
    - distributions are added to template
    - QCD measured with data
    - EWK predicted with Monte Carlo  
 $\Delta M_W = 8 \text{ (9) MeV for } e \text{ (\mu)}$
- 
- The Feynman diagram illustrates the process of W boson production. A quark ( $q$ ) and an antiquark ( $\bar{q}$ ) annihilate at a vertex into a virtual photon ( $\gamma$ ). This virtual photon then decays at a vertex into a W boson ( $w^\pm$ ) and an electron ( $e^\pm$ ) or muon ( $\mu^\pm$ ). The W boson subsequently decays at a vertex into a neutrino ( $\nu$ ) and an electron ( $e^\pm$ ) or muon ( $\mu^\pm$ ).
- | Background               | % (Muons)       | % (Electrons)   |
|--------------------------|-----------------|-----------------|
| Hadronic Jets            | $0.1 \pm 0.1$   | $0.25 \pm 0.15$ |
| Decay in Flight          | $0.3 \pm 0.2$   | -               |
| Cosmic Rays              | $0.05 \pm 0.05$ | -               |
| $Z \rightarrow ll$       | $6.6 \pm 0.3$   | $0.24 \pm 0.04$ |
| $W \rightarrow t\bar{n}$ | $0.89 \pm 0.02$ | $0.93 \pm 0.03$ |

# *W Mass Fits*

Transverse mass fits:



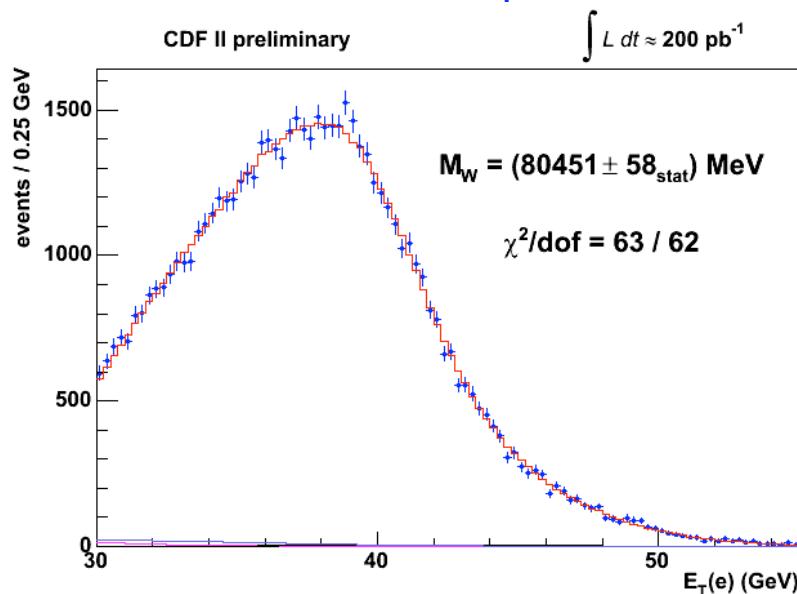
$$m_W = 80417 \pm 48 \text{ MeV (stat + syst)}$$

combination yields  $P(\chi^2) = 7\%$

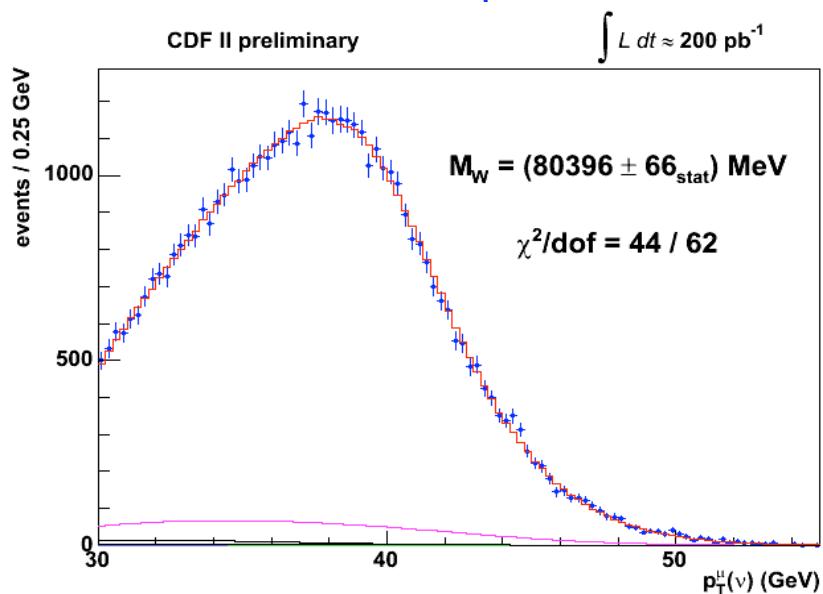
## W Mass Fits

Also fit  $E_T$  and  $\not{E}_T$  distributions in muon and electron channel and combine with transverse mass fits:

Electron  $E_T$  fit



Muon  $\not{E}_T$  fit



$$m_W = 80413 \pm 48 \text{ MeV (stat + syst)}$$

combination of all six fits yields  $P(\chi^2) = 44\%$

## Systematic Uncertainty

Systematic uncertainty on transverse mass fit

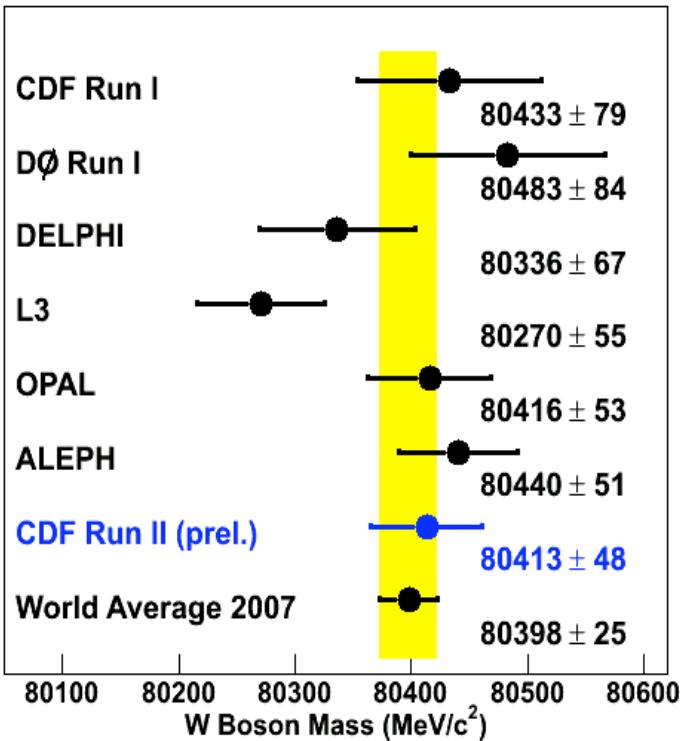
CDF II preliminary

$L = 200 \text{ pb}^{-1}$

$m_T$ Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{  }$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
<b>Total</b>	<b>62</b>	<b>60</b>	<b>26</b>

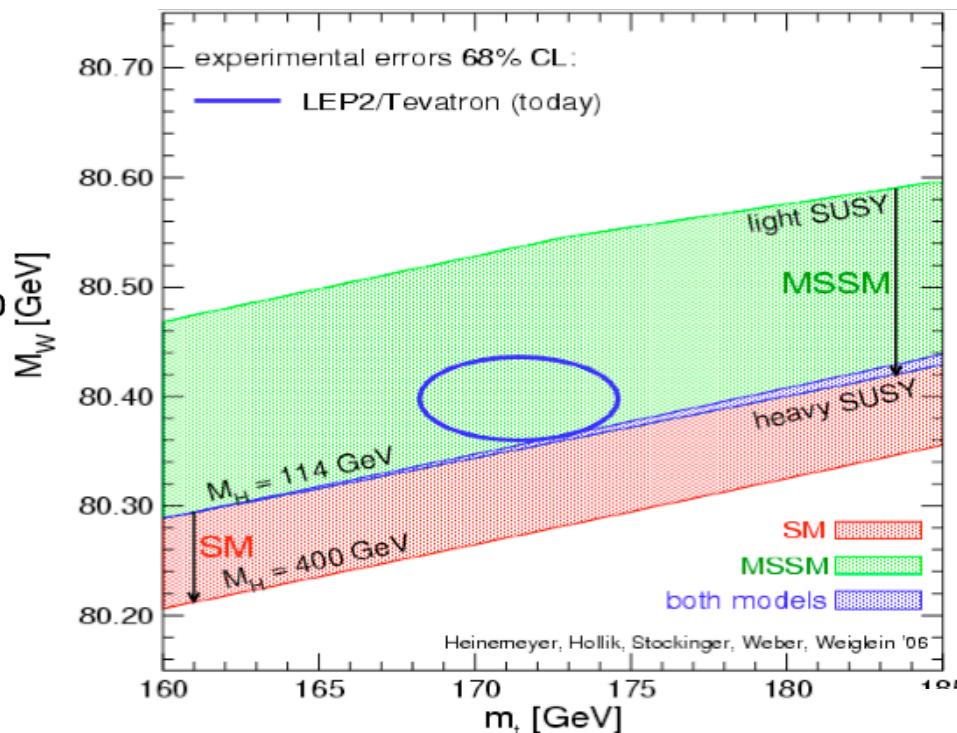
⇒ Combined Uncertainty: 48 MeV for 200 pb<sup>-1</sup>

# Results



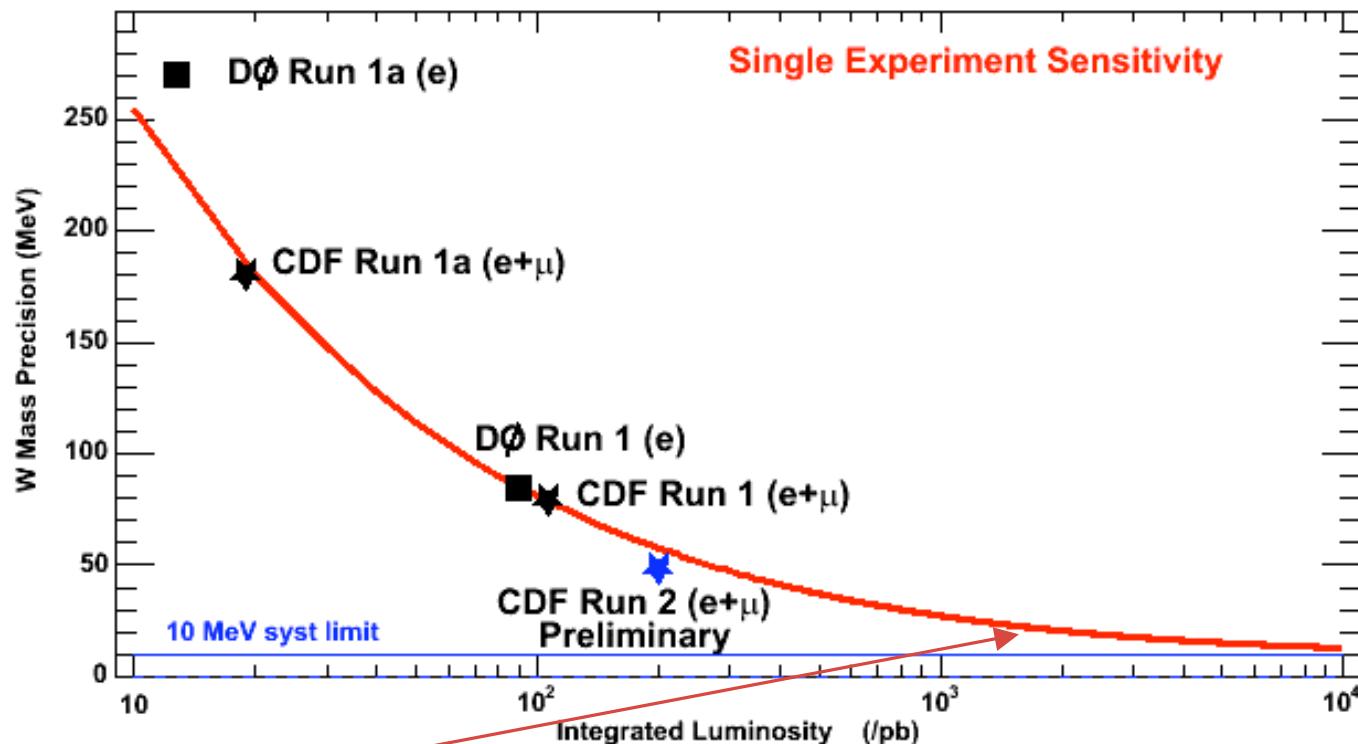
- Standard Model Higgs constraint:  $80^{+36}_{-26}$  GeV (previous:  $85^{+39}_{-28}$  GeV)

- New CDF result is the world's most precise single measurement
- World average increases: 80392 to 80398 MeV
- Uncertainty reduced ~15% (29 to 25 MeV)



## Summary/Outlook

- First Run II W mass measurement completed using  $200 \text{ pb}^{-1}$  of data
- With a total uncertainty of 48 MeV  
→ worlds most precise single measurement
- Projection from previous Tevatron measurements



- Expect  $\Delta M_W < 25 \text{ MeV}$  with  $1.5 \text{ fb}^{-1}$  already collected

# *Backup*

# Systematic Uncertainty

CDF II preliminary				$L = 200 \text{ pb}^{-1}$				CDF II preliminary				$L = 200 \text{ pb}^{-1}$			
$p_T$ Uncertainty [MeV]	Electrons	Muons	Common	$p_T$ Uncertainty [MeV]	Electrons	Muons	Common	$p_T$ Uncertainty [MeV]	Electrons	Muons	Common	$p_T$ Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17	Lepton Scale	30	17	17	Lepton Scale	30	17	17	Lepton Scale	30	17	17
Lepton Resolution	9	3	0	Lepton Resolution	9	5	0	Lepton Resolution	9	5	0	Lepton Resolution	9	5	0
Recoil Scale	17	17	17	Recoil Scale	15	15	15	Recoil Scale	15	15	15	Recoil Scale	15	15	15
Recoil Resolution	3	3	3	Recoil Resolution	30	30	30	Recoil Resolution	30	30	30	Recoil Resolution	30	30	30
$u_{  }$ Efficiency	5	6	0	$u_{  }$ Efficiency	16	13	0	$u_{  }$ Efficiency	16	13	0	$u_{  }$ Efficiency	16	13	0
Lepton Removal	0	0	0	Lepton Removal	16	10	10	Lepton Removal	16	10	10	Lepton Removal	16	10	10
Backgrounds	9	19	0	Backgrounds	7	11	0	Backgrounds	7	11	0	Backgrounds	7	11	0
$p_T(W)$	9	9	9	$p_T(W)$	5	5	5	$p_T(W)$	5	5	5	$p_T(W)$	5	5	5
PDF	20	20	20	PDF	13	13	13	PDF	13	13	13	PDF	13	13	13
QED	13	13	13	QED	9	10	9	QED	9	10	9	QED	9	10	9
Total Systematic	45	40	35	Total Systematic	54	46	42	Total Systematic	54	46	42	Total Systematic	54	46	42
Statistical	58	66	0	Statistical	57	66	0	Statistical	57	66	0	Statistical	57	66	0
Total	73	77	35	Total	79	80	42	Total	79	80	42	Total	79	80	42

# *Signed $\chi$*

